

Robust quantum repeater with atomic ensembles and single-photon sources

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We present a quantum repeater protocol using atomic ensembles, linear optics and single-photon sources. Two local 'polarization' entangled states of atomic ensembles u and d are generated by absorbing a single photon emitted by an on-demand single-photon sources, based on which high-fidelity local entanglement between four ensembles can be established efficiently through Bell-state measurement. Entanglement in basic links and entanglement connection between links are carried out by the use of two-photon interference. In addition to being robust against phase fluctuations in the quantum channels, this scheme may speed up quantum communication with higher fidelity by about 2 orders of magnitude for 1280 km compared with the partial read (PR) protocol (Sangouard *et al.*, Phys. Rev. A **77**, 062301 (2008)) which may generate entanglement most quickly among the previous schemes with the same ingredients.

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Entanglement plays a fundamental role in quantum information science [1] because it is a crucial requisite for quantum metrology [2], quantum computation [3, 4], and quantum communication [3, 5]. Because of losses and other noises in quantum channels, the communication fidelity falls exponentially with the channel length. In principle, this problem can be overcome by applying quantum repeaters [5, 6, 7, 8, 9, 10], in which initial imperfect entangled pairs are established over elementary links, these initial pairs are then purified to high fidelity entanglement and connected through quantum swaps [11, 12] with doubled quantum communication length. With the quantum repeater protocol one may generate high fidelity long-distance entanglement with resources increasing only polynomially with communication distance. A protocol of special importance for long-distance quantum communication with atomic ensemble as local memory qubits and linear optics is proposed in a seminal paper of Duan *et al.* [13]. After that considerable efforts have been devoted along this line [14, 15, 16, 17, 18, 19, 20].

In addition to using relatively simple ingredients, DLCZ protocol has built-in entanglement purification and thus is tolerant against photon losses. However, entanglement generation and entanglement connection in the DLCZ protocol is based on a single-photon Mach-Zehnder-type interference, resulting the relative phase in the entangled state of two distant ensembles is very sensitive to path length instabilities [19, 21]. Moreover, entanglement generation is created by detecting a single photon from one of two ensembles. The probability of generating one excitation in two ensembles denoted by p is related to the fidelity of the entanglement, leading to the condition $p \ll 1$ to guaranty an acceptable quality of the entanglement. But when $p \rightarrow 0$, some experimental imperfections such as stray light scattering and detector dark counts will contaminate the entangled state increasingly [20], and subsequent processes including quantum swap and quantum communication become more challenging for finite coherent time of quantum memory [16].

In recent papers [19, 21], Chen *et al.* suggest a robust quan-

tum repeater protocol which is insensitive to the path length phase instabilities by using the two-photon Hong-Ou-Mandel-type (HOMT) interference rather than single-photon interference. Sangouard *et al.* [22] developed that protocol by exploiting a more efficient method of generating entangled pairs locally with partial readout of the ensemble-based memories, which makes it generate entanglement most quickly among the previous schemes with the same ingredient. However, to achieve a high communication rate atomic ensembles have to be excited with a very high repetition rate because of the very low probability p . Here we propose a quantum repeater strategy based on the DLCZ scheme. In this strategy, the local entangled state between two atomic ensembles is established by storage a sharing photon from an on-demand single-photon source [16, 23, 24], which may release the stringent condition on p , both of initial entanglement states in basic links and entanglement connection between links are carried out through detection of the two-photon HOMT interference. Besides being insensitive to phase fluctuations in the quantum channels, this scheme may enhance quantum communication with near unity fidelity by about 2 orders of magnitude for 1280 km compared with the PR protocol.

An atomic ensemble consists of a cloud of N_a identical atoms with pertinent level structure shown in Fig. 1 a. One ground state $|g\rangle$ and two metastable states $|s\rangle$ and $|t\rangle$ may be provided by, for instance, hyperfine or Zeeman sublevels of the electronic ground state of alkali-metal atoms, where long relevant coherent lifetime has been observed [25, 26, 27]. The atomic ensemble is optically thick along one direction to enhance the coupling to light [13]. State $|e_1\rangle$ is an excited state. Let us consider two sites L and R at every node shown in Fig. 1. Each site has two atomic ensembles u and d acting as one memory qubit. A single photon emitted with a repetition rate r from an on-demand single-photon source [16, 28] located halfway between atomic ensembles u and d is split into an entangled state of optical modes u_{in} and d_{in} (Fig. 1 b)

$$|\psi_{in}(\phi)\rangle = \frac{1}{\sqrt{2}} \left(|0\rangle_{u_{in}} |1\rangle_{d_{in}} + e^{i\phi} |1\rangle_{u_{in}} |0\rangle_{d_{in}} \right) \quad (1)$$

the coincidences of the two single-photon detectors D_1 and D_4 (D_1 and D_3) or D_2 and D_3 (D_2 and D_4) are recorded, so the protocol is successful only if each of the paired detectors have a click. Under this circumstance, the vacuum components in the EME states, one-excitation components like $S_{L_u}^\dagger |vac\rangle$, and the two-excitation components $T_{L_u}^\dagger T_{R_d}^\dagger |vac\rangle$ and $T_{L_d}^\dagger T_{R_u}^\dagger |vac\rangle$ have no effect on the experimental results, where $|vac\rangle$ is the ground state of the ensemble $|0_a\rangle_{u_L}|0_a\rangle_{d_L}|0_a\rangle_{u_R}|0_a\rangle_{d_R}$. A coincidence click between single-photon detectors, for example, D_1 and D_4 will project the two memory qubits into the polarization maximally entangled (PME) state [21, 34]

$$|\Psi\rangle_{LR} = \frac{1}{\sqrt{2}}(S_{u_L}^\dagger S_{u_R}^\dagger + S_{d_L}^\dagger S_{d_R}^\dagger)|vac\rangle. \quad (6)$$

The success probability for entanglement generation at every node is $p_l = \eta_p^2 \eta_s^2 \eta_e^2 \eta_d^2 / 2$, where η_{e1} denotes the efficiency for the atomic ensemble emitting a photon during the process $T^\dagger|0_a\rangle \rightarrow S^\dagger|0_a\rangle$ and η_d denotes the single-photon detection efficiency. The average waiting time for successful generating a local entanglement state is $T_l = \frac{1}{rp_l}$.

After local entanglement states are established, one can generate an entangled state in a basic link with nodes A and B at a distance L_0 using BSM illustrated in Fig. 3. By applying a retrieval pulse of suitable polarization that is near-resonant to the atomic transition $|s\rangle \rightarrow |e_3\rangle$, the atomic excitation S in the atom ensemble can be converted into light which has polarization and frequency different from the retrieval pulse. The efficiency of this transfer denoted by η_{e2} can be very close to unity because of collective enhancement [13, 26, 29, 32, 33]. When four atomic ensembles are illuminated by the retrieval pulses, the anti-stokes photons from memory qubits at A_R and B_L are directed to the polarization beam splitter (PBS) and subject to BSM. The coincident clicks between single-photon detectors D_1 and D_4 (D_1 and D_3) or D_2 and D_3 (D_2 and D_4) will project the two memory qubits into the PME state

$$|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}(S_{A_{L_u}}^\dagger S_{B_{R_u}}^\dagger + S_{A_{L_d}}^\dagger S_{B_{R_d}}^\dagger)|vac\rangle \quad (7)$$

up to a local unitary transformation [21, 34]. The protocol is successful if, and only if these coincident clicks occur with a probability $p_0 = \eta_{e2}^2 \eta_e^2 \eta_d^2 / 2$, where $\eta_t = \exp[-L_0/(2L_{att})]$ is the fiber transmission with the attenuation length L_{att} .

After successful generating entanglement within basic links, we can extend the quantum communication distance through entanglement swapping with the configuration shown in Fig. 4. We have two pairs of ensembles— A_u, A_d, B_{L_u} , and B_{L_d} , and B_{R_u}, B_{R_d}, C_u , and C_d , located at three sites A , B , and C . Each pair of ensembles is prepared in the PME state in the form of Eq.(7). The stored atomic excitations of four neighboring atomic ensembles B_{L_u} , and B_{L_d} , and B_{R_u}, B_{R_d} are transferred into light simultaneously with the retrieve pulses. We also assume the polarizations of the anti-stokes photons produced from the u ensemble and d ensemble are orthogonal. The stimulated optical excitations are then subject to BSM at the middle point. If, and only if coincident clicks between detectors D_1 and D_4 (D_1 and D_3) or D_2 and D_3 (D_2

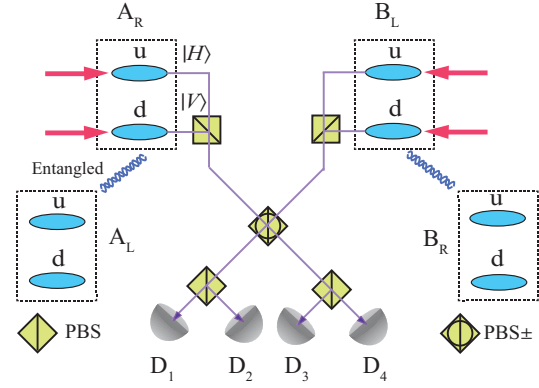


FIG. 3: (Color online) Schematic illustration of entanglement generation between two nodes A and B via BSM. The memory qubits at sites (A_L, A_R) and (B_L, B_R) are prepared in the PME states in the form of equation (6). With the memory qubits at sites A_R and B_L illuminated by near resonant retrieve pulses the anti-Stokes photons are generated with different polarizations $|H\rangle$ from u ensembles and $|V\rangle$ from d ensembles, and subject to BSM at the midpoint. Up to a local unitary phase shift the coincident count between D_1 and D_4 (D_1 and D_3) or D_2 and D_3 (D_2 and D_4) will project the memory qubits into a PME state between sites A_L and B_R .

and D_4) occur, the protocol is successful with a probability $p_1 = \frac{1}{2}\eta_{e2}^2 \eta_e^2 \eta_d^2$ and an entangled state in the form of equation (7) is established among the ensembles A_u, A_d, C_u , and C_d with a doubled communication distance. Otherwise, we need to repeat the previous process of entanglement generation and swapping.

The scheme for entanglement swapping can be applied to arbitrarily extend the communication distance. For the i th ($i = 1, 2, \dots, n$) entanglement swapping, we first prepare simultaneously two pairs of ensembles in the PME state with the same communication length L_{i-1} , and then make entanglement swapping as shown by Fig. 4 with a success probability $p_i = \frac{1}{2}\eta_{e2}^2 \eta_e^2 \eta_d^2$. After a successful entanglement swapping, a new PME state is established and the communication length is extended to $L_i = 2L_{i-1}$. Since the i th entanglement swapping needs to be repeated on average $1/p_i$ times, the average total time needed to generating a PME state over the distance $L = L_n = 2^n L_0$ is given by

$$T_{tot} = \frac{T_0}{\prod_{i=0}^n p_i} \quad (8)$$

where $T_0 = L_0/c + T_l$ with c being the light speed in the optical fiber.

For the prototype two-photon-based protocol and the PR protocol, the established local entangled states are mixed states due to higher-order excitations in the atomic ensembles. Thanks to applying on-demand single-photon sources, the higher-order excitations can be arbitrarily suppressed with unending advances in single-photon sources [28, 35], resulting the fidelity of local entanglement and the final long-distance entanglement approaching unity when there are no other imperfections. In our scheme, the probability of generating an

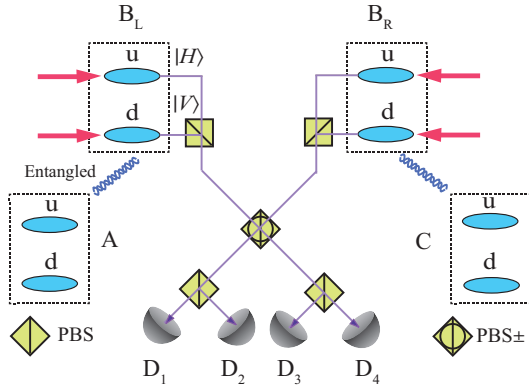


FIG. 4: (Color online) Schematic illustration of entanglement connection between two nodes A and C via entanglement swapping. The memory qubits at sites (A, B_L) and (B_R, C) are prepared in the PME states in the form of equation (7). With the memory qubits at sites B_L and B_R illuminated by near resonant retrieve pulses the anti-Stokes photons are generated with different polarizations $|H\rangle$ from u ensembles and $|V\rangle$ from d ensembles, and subject to BSM at the midpoint. Up to a local unitary phase shift the coincidence count between D_1 and D_4 (D_1 and D_3) or D_2 and D_3 (D_2 and D_4) will project the memory qubits at sites A and C into a PME state with a double communication length.

atomic excitation via absorbing a photon from an on-demand single-photon sources does not have to meet the condition $p \ll 1$. Considering the efficiency of the transfer of T into S η_{e1} may be low, we assume $\eta_{e1} = 0.05$. Assuming that $r = 39.2$ MHz, $\eta_p = 0.9$, $\eta_s = 0.9$, $\eta_{e2} = 0.9$, $\eta_d = 0.9$, $L = 1280$ km, $L_{att} = 22$ km for photons with wavelength of $1.5 \mu\text{m}$ [24], $c = 2.0 \times 10^5$ km/s, and $n = 4$, equation (8) gives the average total time $T_{tot} = 4.4$ s. For comparison reason, we estimate the average total time $T_{tot} = 107.6$ s for the PR protocol [22] with the above relevant parameters in addition to the probability $p = 0.006$ to obtain entanglement fidelity $F = 0.9$ [22]. With the above parameters, to equate local entanglement preparation time T_l with the communication time L_0/c , we have the repetition rate $r = 3.76$ MHz for this new scheme and $r = 39.2$ MHz for the PR protocol. Note that the possibility of high repetition rate of pulse acting on atomic ensembles remains an open question, since only a repetition rate $r = 250$ KHz is reported by Chou *et al.* [36]. As for this new scheme, the requirement of repetition rate r is weak, at the same time we note that η_{e1} can be enhanced by putting the atomic ensembles in a low-finesse ring cavity [13] and one can exploited many kinds of on-demand single-photon sources, such as molecule-based sources with max rate 100 MHz and quantum-dot-based sources with max rate 1 GHz [35]. In this scheme, average total time $T_{tot} = 0.84$ s can be reached with optimal number of links $n = 6$ and the same aforementioned relevant parameters for $L = 1280$ km. Thus through this scheme quantum communication with higher fidelity may be sped up by about two orders of magnitude for 1280 km compared with that based on the PR protocol.

Now we discuss imperfections in our architecture for quan-

tum entanglement distribution. We have shown that this strategy has no inherent error mechanism, that is, the fidelity of the obtained entanglement will be unity provided that all components of the setup work perfectly. In the whole process of entanglement generation, connection, the photon losses includes contributions from channel absorption, spontaneous emissions in atomic ensembles, conversion inefficiency of single-photon into and out of atomic ensembles, and inefficiency of single-photon detectors. These losses decreases the success probability but has no effect on the fidelity of the established entanglement. Main imperfection is due to dark counts, which means that detector clicks in the absence of photons. When a dark count occurs in either the stage of basic entanglement generation or that of entanglement connection, one can exploits photon-number-resolved single-photon detector to exclude this case according to repeater protocol. If a dark count occurs in the process of local entanglement preparation, the local entangled state is a mixed state with a contribution from one atomic excitation, resulting the fidelity of the generated long-distance entanglement decreases. Considering that the probability for a detector to give a dark count denoted by p_d smaller than 5×10^{-6} is within the reach of the current techniques [24], we can estimate the fidelity imperfection $\Delta F \equiv 1 - F$ for the generated long-distance entanglement by

$$\Delta F = 2^{n+1} p_d < 1.6 \times 10^{-4} \quad (9)$$

for $n = 4$. Further note that this scheme is compatible with the linear optics entanglement purification protocol introduced in the manuscript [37].

In conclusion, we have proposed a scheme for long-distance entanglement distribution based on two-photon-interference and single-photon sources. Through this scheme, the rate of long-distance quantum communication can increase by about two orders of magnitude for 1280 km compared with the PR protocol. At the same time, this scheme is robust against path length instabilities and near unity fidelity of generated entanglement may be expected. Considering the simplicity of the physical set-ups used, this scheme may opens up the probability of efficient long-distance quantum communication.

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